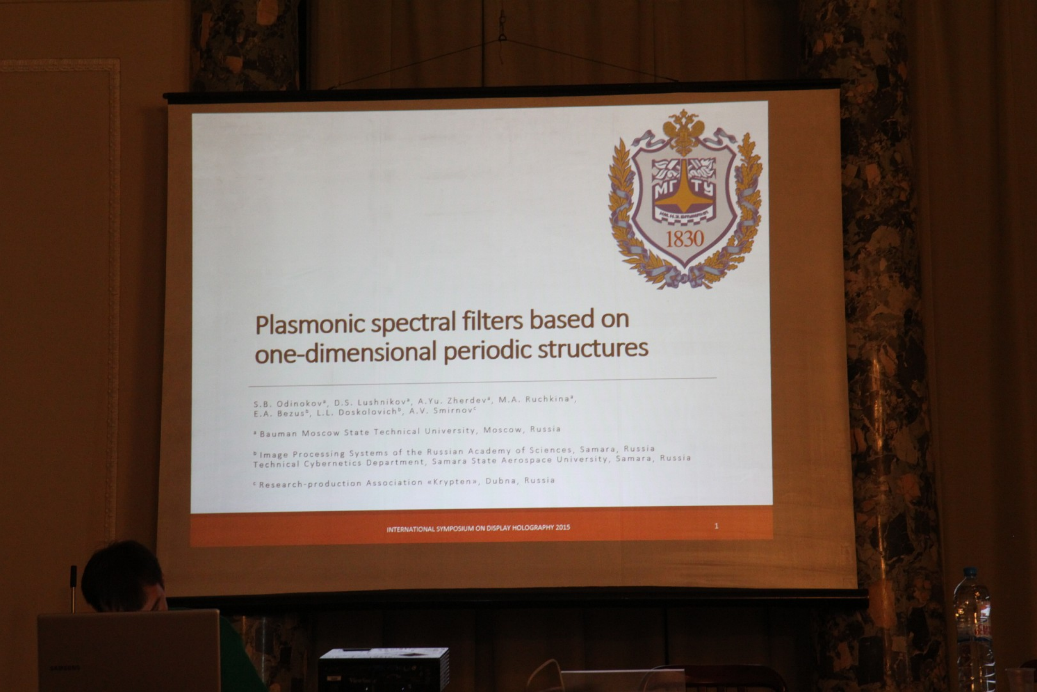

МГ ТУ
1830
Plasmonic spectral filters based on one-dimensional periodic structures
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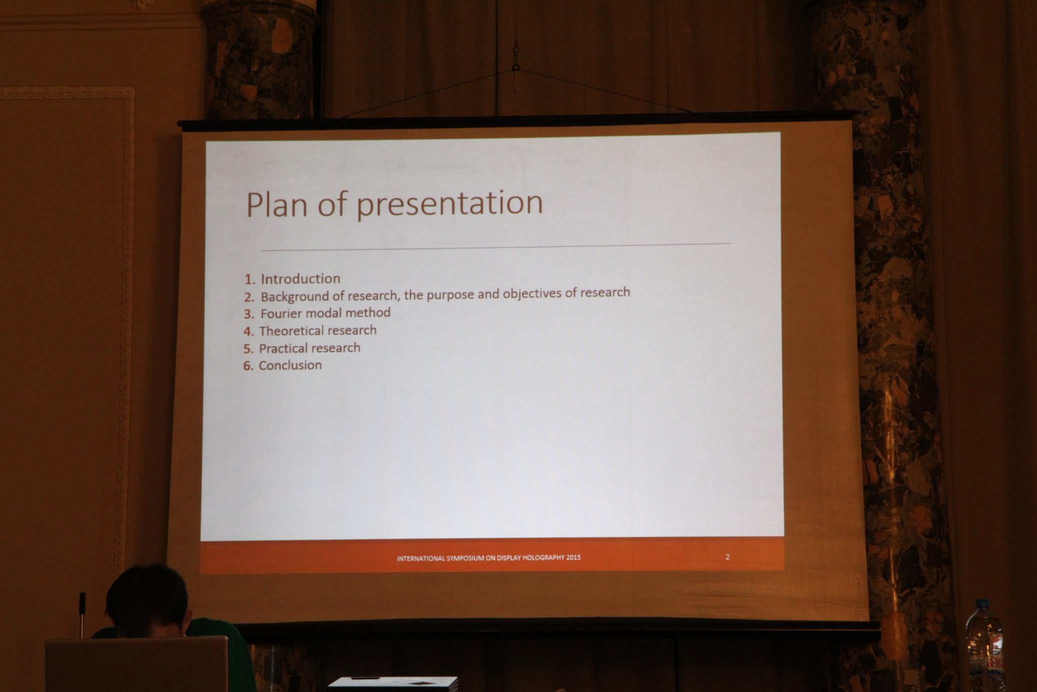
Plan of presentation
1. Introduction
2. Background of research, the purpose and objectives of research
3. Fourier modal method
4. Theoretical research
5. Practical research
6. Conclusion
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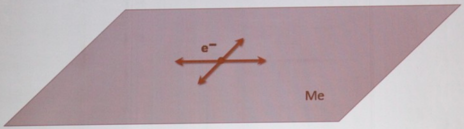
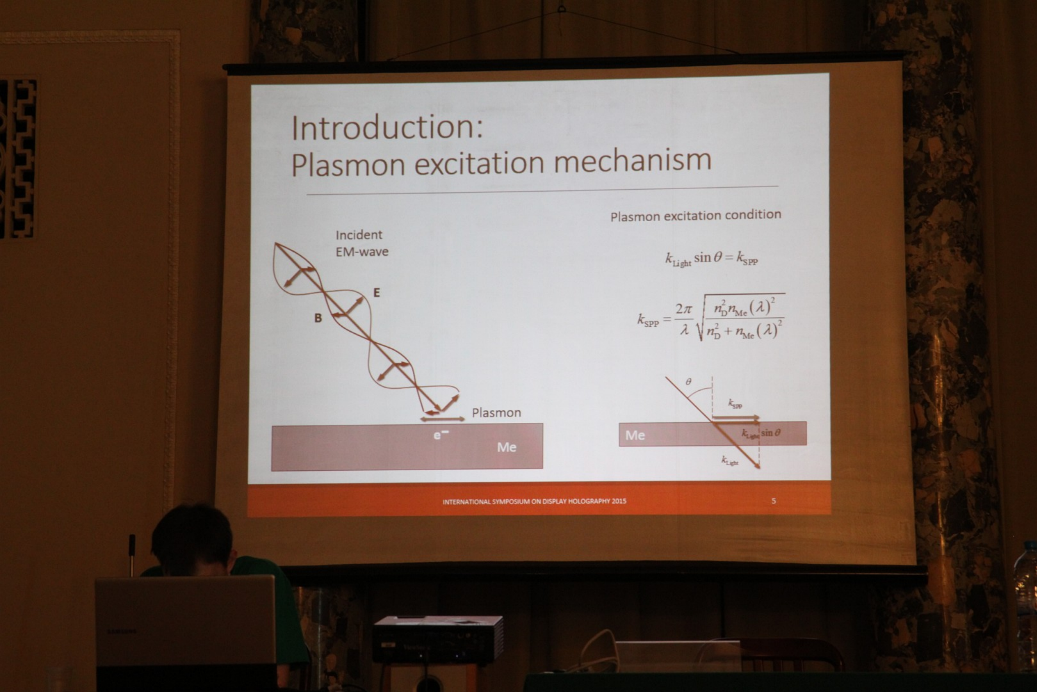
Introduction: What is plasmon?

Plasmon — quasiparticle corresponding to quantum of oscillations of the free electron gas (oscillations of electron plasma).

Surface plasmon exists on a metal—dielectric interface




Introduction:
Plasmon excitation mechanism
Incident
EM-wave
E
B
Plasmon
e⁻
Me
Plasmon excitation condition
$k_{\text{Light}} \sin\theta = k_{\text{SPP}}$
$k_{\text{SPP}} = \frac{2\pi}{\lambda}\sqrt{\frac{n_{\text{D}}^2 n_{\text{Me}}(\lambda)^2}{n_{\text{D}}^2 + n_{\text{Me}}(\lambda)^2}}$
θ
k_{SPP}
Me
$k_{\text{Light}} \sin\theta$
k_{Light}
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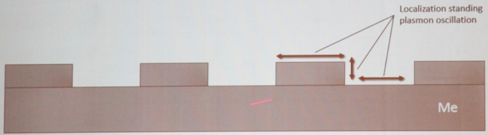
Introduction: Plasmon resonance

Plasmon resonance — excitation of surface plasmon at resonance frequency by incident electromagnetic wave.

Possible condition:

- ❖ Total internal reflection— traveling wave
- ❖ Localization of plasmon in nanostructures — standing wave

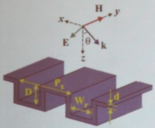


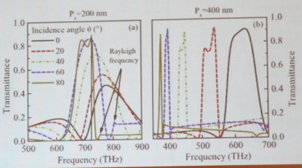
Plasmonic spectral filter by Liwei Fu

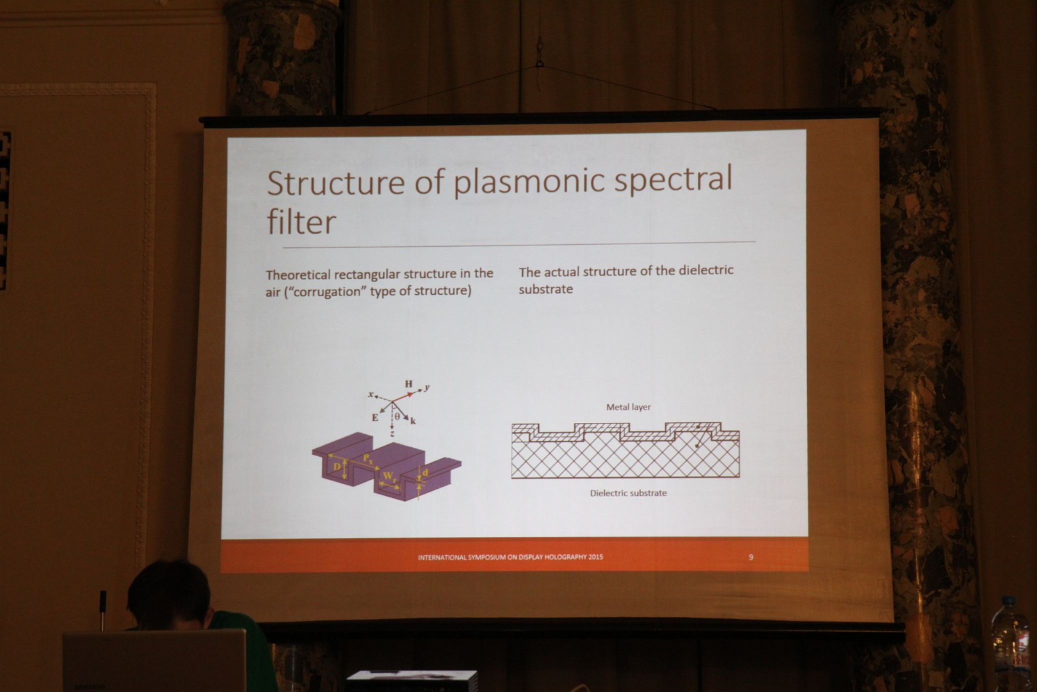
(Optical properties of metallic meanders, Liwei Fu, Heinz Schweizer, Thomas Weiss, and Harald Giessen, J. Opt. Soc. Am. B 26, B111-B119, 2009)

- Period: from 200 to 400 nm
- Height: 40 nm
- Ag thickness: 40 nm
- Angle of incident: from 0° to 80°

✓ Broadband spectral filters
✓ Work on the transmission
✓ In a wide range of angles of incidence






Structure of plasmonic spectral filter
Theoretical rectangular structure in the air ("corrugation" type of structure)
The actual structure of the dielectric substrate
H
y
x
E
θ
k
z
D
P
W
d
Metal layer
Dielectric substrate
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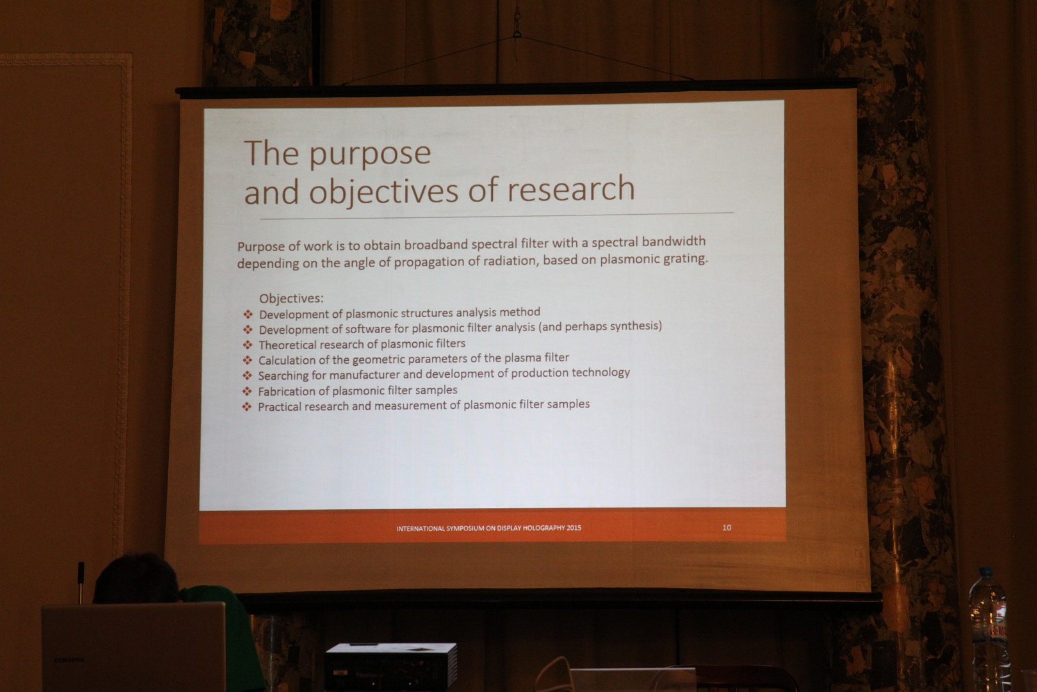
The purpose and objectives of research
Purpose of work is to obtain broadband spectral filter with a spectral bandwidth depending on the angle of propagation of radiation, based on plasmonic grating.
Objectives:
Development of plasmonic structures analysis method
Development of software for plasmonic filter analysis (and perhaps synthesis)
Theoretical research of plasmonic filters
Calculation of the geometric parameters of the plasma filter
Searching for manufacturer and development of production technology
Fabrication of plasmonic filter samples
Practical research and measurement of plasmonic filter samples
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Fourier modal method

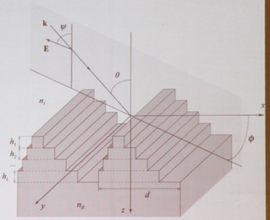
Maxwell's equations and constitutive equation

$$\begin{cases} \mathrm{rot}\,\mathbf{H} = \dfrac{4\pi}{c}\mathbf{j} + \dfrac{1}{c}\dfrac{\partial \mathbf{D}}{\partial t} \\ \mathrm{rot}\,\mathbf{E} = -\dfrac{1}{c}\dfrac{\partial \mathbf{B}}{\partial t} \\ \mathrm{div}\,\mathbf{D} = 4\pi\rho \\ \mathrm{div}\,\mathbf{B} = 0 \end{cases} \qquad \begin{cases} \mathbf{D} = \varepsilon\mathbf{E} \\ \mathbf{B} = \mu\mathbf{H} \\ \mathbf{j} = \sigma\mathbf{E} \end{cases}$$

Incident wave

$$\mathbf{E}_{inc} = \mathbf{u}\exp\left[ik_0 n_I\left(\sin\theta\cos\phi x + \sin\theta\sin\phi y + \cos\theta z\right)\right]$$

$$\mathbf{u} = \begin{pmatrix} \cos\psi\cos\theta\cos\phi - \sin\psi\sin\phi \\ \cos\psi\cos\theta\sin\phi + \sin\psi\cos\phi \\ -\cos\psi\sin\theta \end{pmatrix}$$



Fourier modal method

Incident wave

$$\mathbf{E}_{inc} = \mathbf{u}\exp\left[ik_0 n_I\left(\sin\theta\cos\phi x + \sin\theta\sin\phi y + \cos\theta z\right)\right]$$

$$\mathbf{u} = \left(\cos\psi\cos\theta\cos\phi - \sin\psi\sin\phi, \cos\psi\cos\theta\sin\phi + \sin\psi\cos\phi, -\cos\psi\sin\theta\right)$$

Representation of the field above and below the structure (as Rayleigh series):

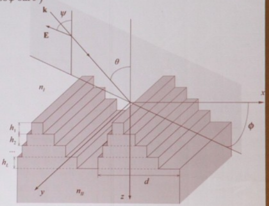
$$\mathbf{E}_I = \mathbf{E}_{inc} + \sum_m \mathbf{R}_m \exp\left[i\left(k_{xm}x + k_y y - k_{I,zm}z\right)\right]$$

$$\mathbf{E}_{II} = \sum_m \mathbf{T}_m \exp\left\{i\left[k_{xm}x + k_y y + k_{II,zm}\left(z - H_L\right)\right]\right\}$$

Representation of the field inside the structure:

$$\mathbf{E}_{l,g} = -i\sum_m\left[S_{l,xm}(z)\mathbf{x} + S_{l,ym}(z)\mathbf{y} + S_{l,zm}(z)\mathbf{z}\right]\exp\left[i\left(k_{xm}x + k_y y\right)\right]$$

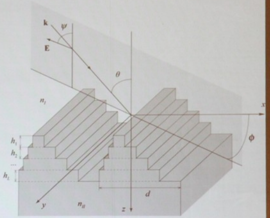
$$\mathbf{H}_{l,g} = \sum_m\left[U_{l,xm}(z)\mathbf{x} + U_{l,ym}(z)\mathbf{y} + U_{l,zm}(z)\mathbf{z}\right]\exp\left[i\left(k_{xm}x + k_y y\right)\right]$$

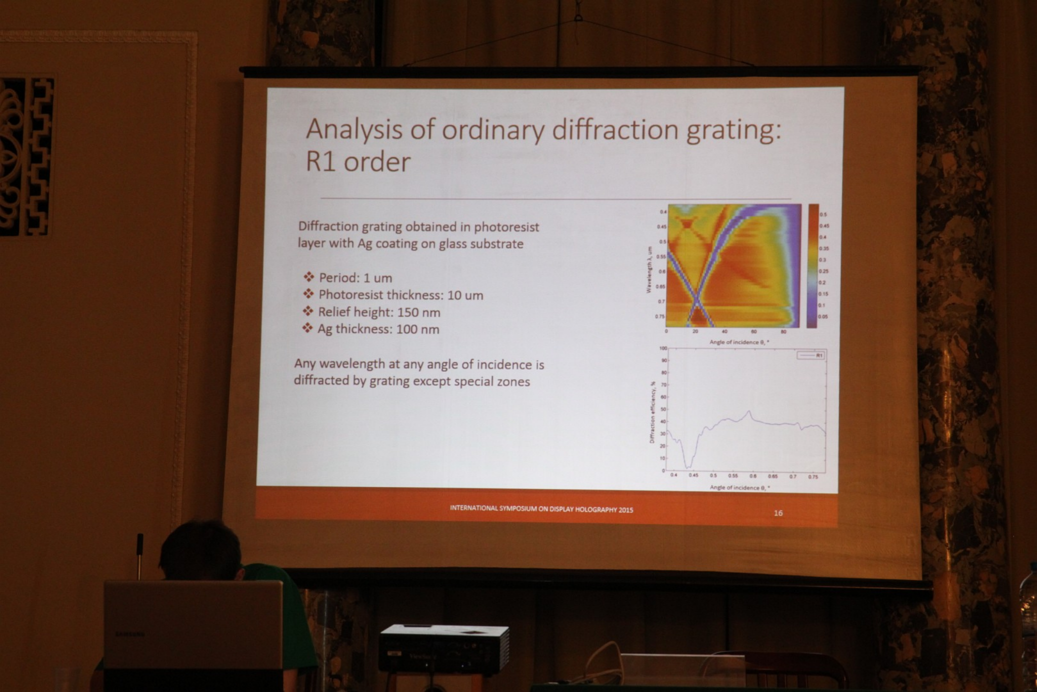


Fourier modal method

Solution algorithm:

- Finding eigenvalues in each layer of structure.
- Applying boundary conditions at interface of structure layers
- Solving of System of linear equations and finding intensity of the transmitted and reflected orders
- The problem is solved in the isotropic on the Oz direction plane-parallel layer of environment




Analysis of ordinary diffraction grating: R1 order
Diffraction grating obtained in photoresist layer with Ag coating on glass substrate
❖ Period: 1 um
❖ Photoresist thickness: 10 um
❖ Relief height: 150 nm
❖ Ag thickness: 100 nm
Any wavelength at any angle of incidence is diffracted by grating except special zones
Wavelength λ, um
Angle of incidence θ, °
R1
Diffraction efficiency, %
Angle of incidence θ, °
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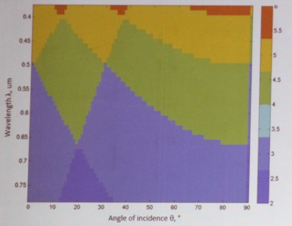
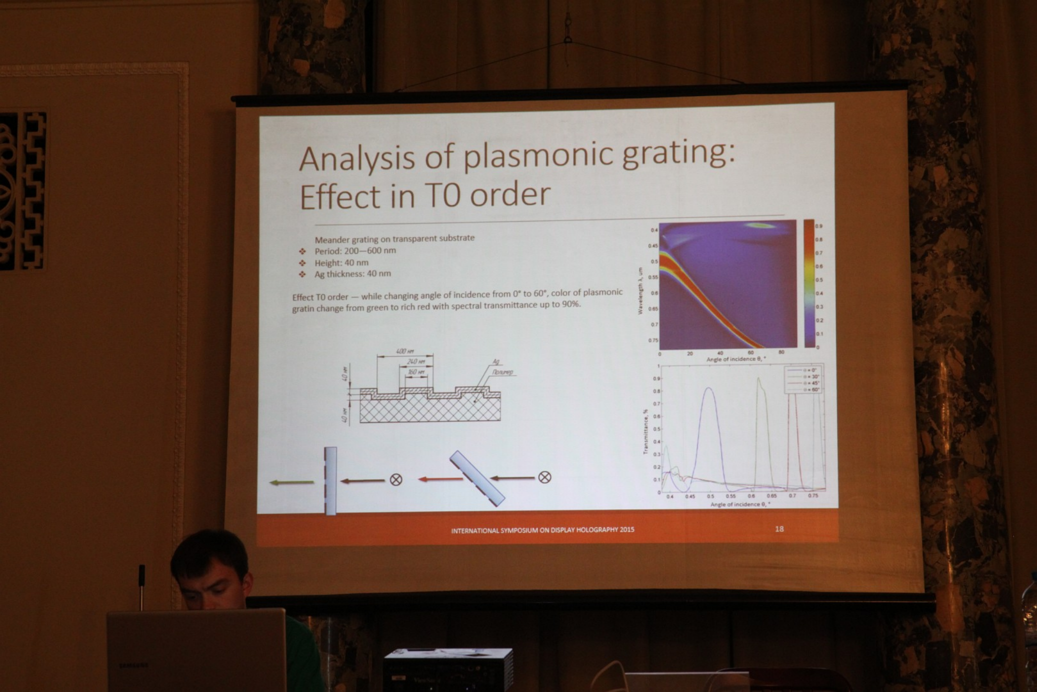
Analysis of ordinary diffraction grating: Diagram of diffraction order number



Plasmonic effect appears at the boundary of region of diffraction order existence


Analysis of plasmonic grating:
Effect in T0 order
Meander grating on transparent substrate
Period: 200—600 nm
Height: 40 nm
Ag thickness: 40 nm
Effect T0 order — while changing angle of incidence from 0° to 60°, color of plasmonic gratin change from green to rich red with spectral transmittance up to 90%.
400 нм
240 нм
160 нм
40 нм
40 нм
Ag
Полимер
Wavelength λ, um
Angle of incidence θ, °
Transmittance, %
Angle of incidence θ, °
θ = 0°
θ = 30°
θ = 45°
θ = 60°
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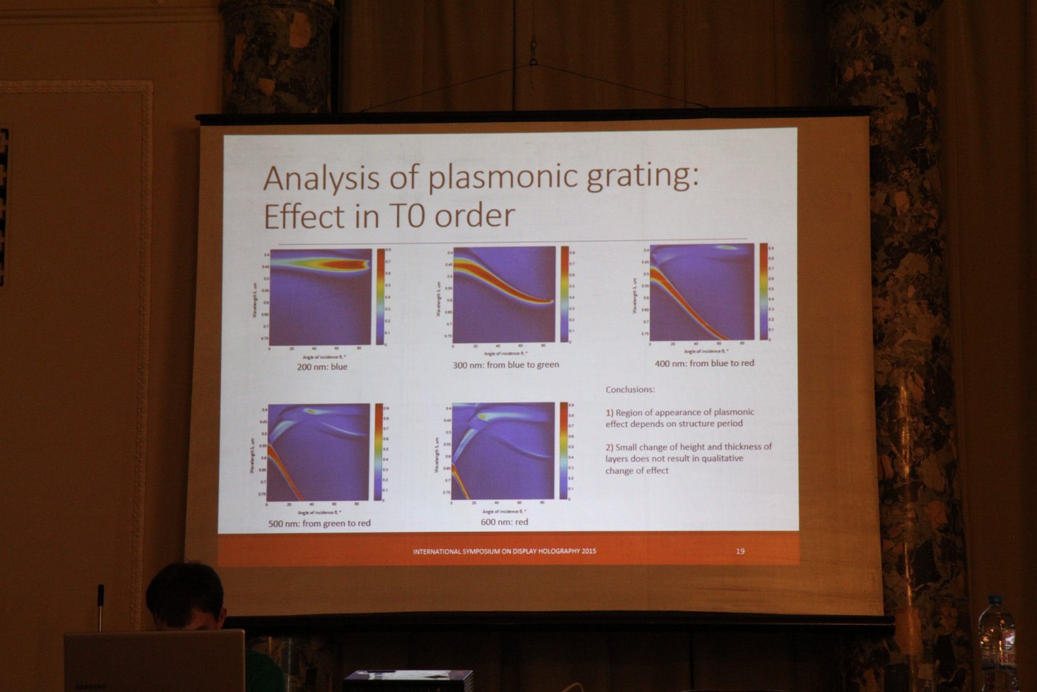

Analysis of plasmonic grating:
Effect in T0 order
200 nm: blue
300 nm: from blue to green
400 nm: from blue to red
500 nm: from green to red
600 nm: red
Conclusions:
1) Region of appearance of plasmonic effect depends on structure period
2) Small change of height and thickness of layers does not result in qualitative change of effect
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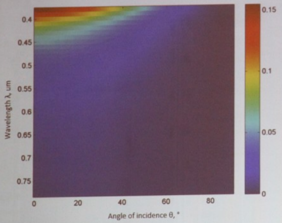
Analysis of plasmonic grating: T0 order in TE-polarized light



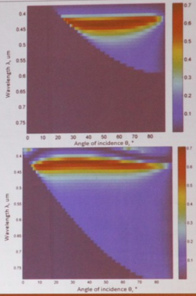
In TE-polarized light there is no plasmonic effect on 1D-periodic structure

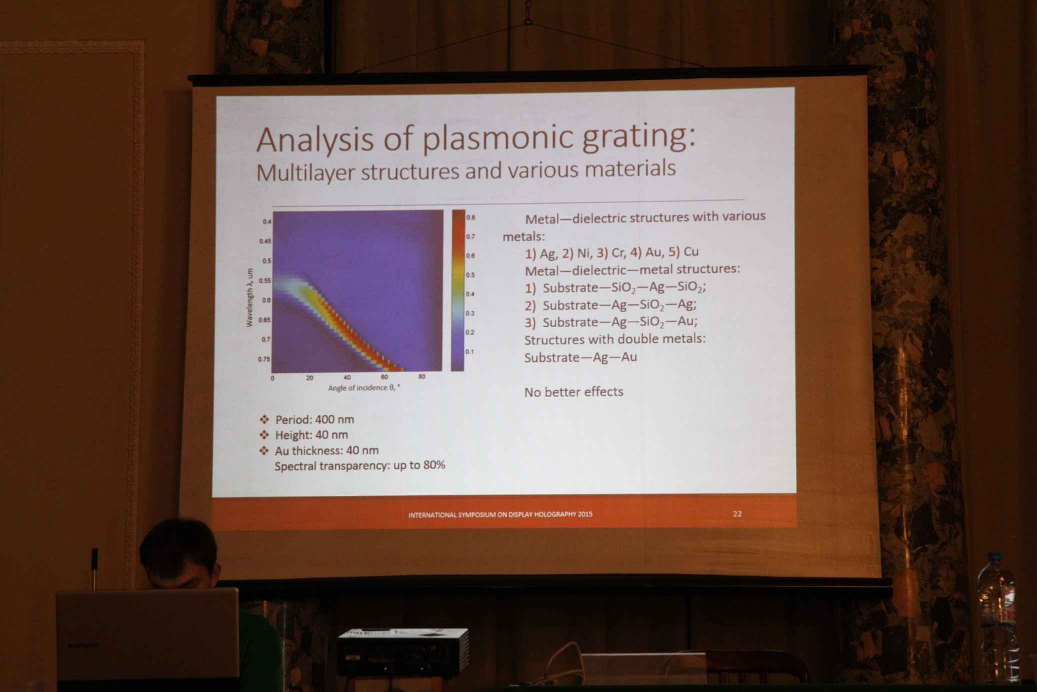
Analysis of plasmonic grating: Effect in R1 order

Plasmonic effect in R1 order

- Period: 300, 400 нм
- Height: 30 нм
- Ag thickness: 80 нм

Effect: while changing the angle of incidence from 10° to 70°, the color of plasmonic grating stays blue with diffraction efficiency up to 70%.





Analysis of plasmonic grating:
Multilayer structures and various materials
Wavelength λ, um
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0
20
40
60
80
Angle of incidence θ, °
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Metal—dielectric structures with various metals:
1) Ag, 2) Ni, 3) Cr, 4) Au, 5) Cu
Metal—dielectric—metal structures:
1) Substrate—SiO_2—Ag—SiO_2;
2) Substrate—Ag—SiO_2—Ag;
3) Substrate—Ag—SiO_2—Au;
Structures with double metals:
Substrate—Ag—Au
No better effects
Period: 400 nm
Height: 40 nm
Au thickness: 40 nm
Spectral transparency: up to 80%
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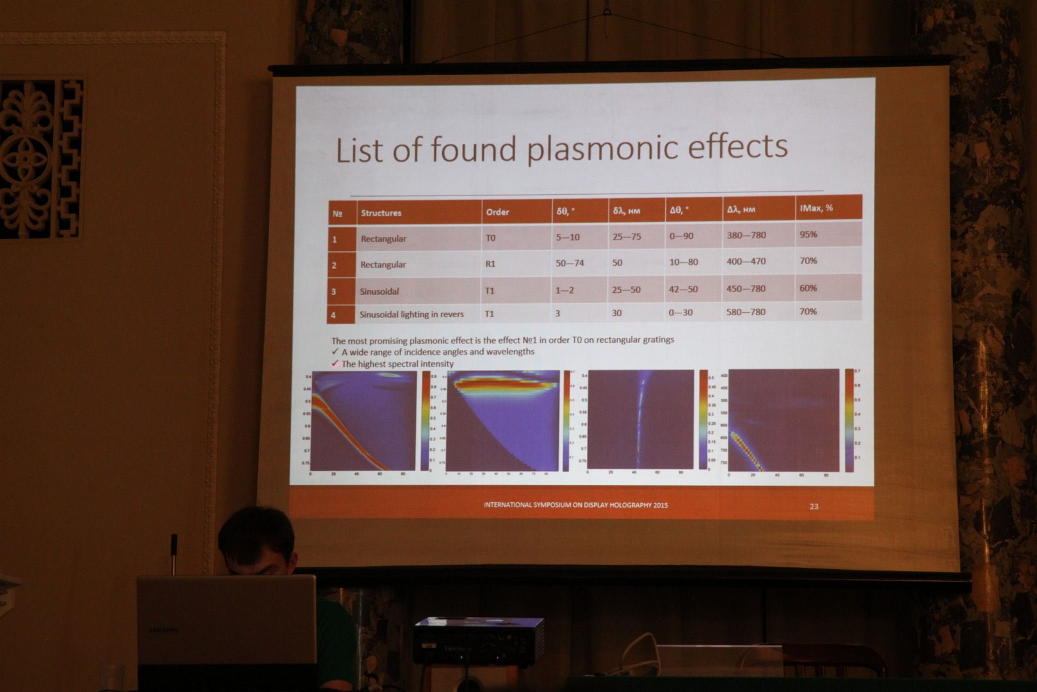
List of found plasmonic effects
№ | Structures | Order | δθ, ° | δλ, нм | Δθ, ° | Δλ, нм | IMax, %
1 | Rectangular | T0 | 5—10 | 25—75 | 0—90 | 380—780 | 95%
2 | Rectangular | R1 | 50—74 | 50 | 10—80 | 400—470 | 70%
3 | Sinusoidal | T1 | 1—2 | 25—50 | 42—50 | 450—780 | 60%
4 | Sinusoidal lighting in revers | T1 | 3 | 30 | 0—30 | 580—780 | 70%
The most promising plasmonic effect is the effect №1 in order T0 on rectangular gratings
✓ A wide range of incidence angles and wavelengths
✓ The highest spectral intensity
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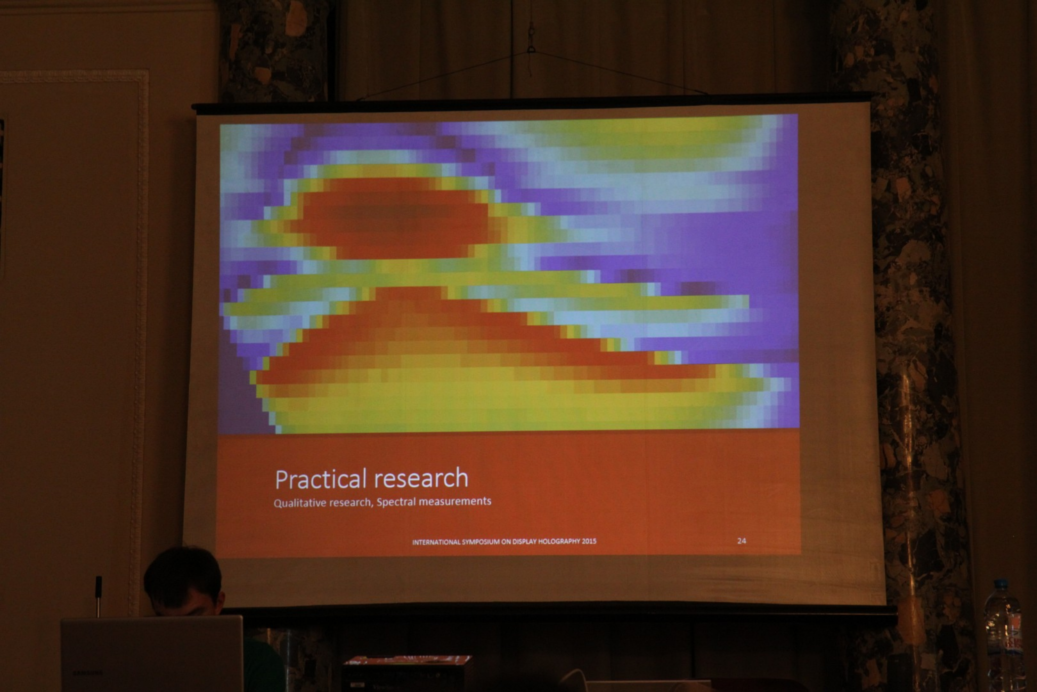

Practical research
Qualitative research, Spectral measurements
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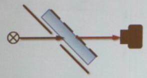
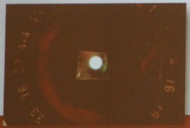
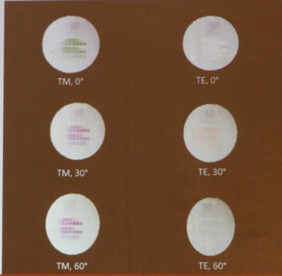
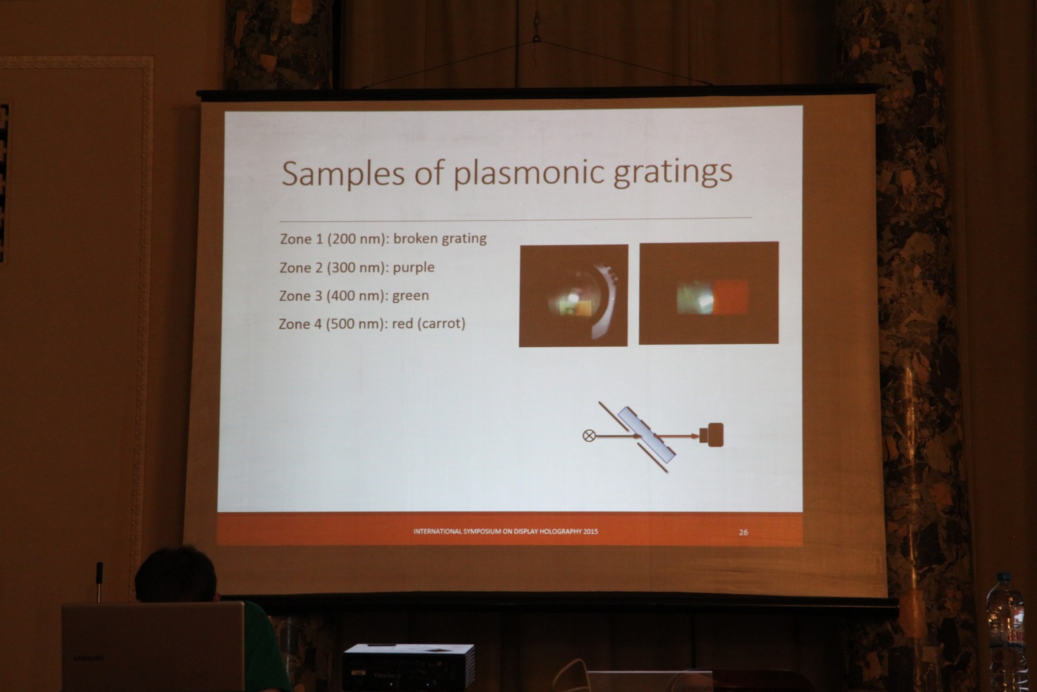
Samples of plasmonic grating: qualitative research

- ✓ Plasmonic effect appears only in TM-polarized (or unpolarized) light
- ✓ When viewed orthogonally, sample is light green
- ✓ When viewed at angle, sample is purple








Samples of plasmonic gratings
Zone 1 (200 nm): broken grating
Zone 2 (300 nm): purple
Zone 3 (400 nm): green
Zone 4 (500 nm): red (carrot)
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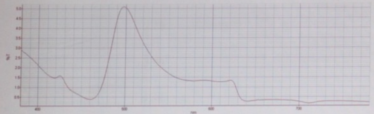
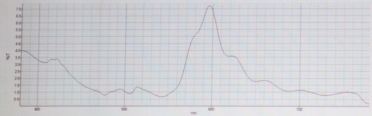
Samples of plasmonic grating: Spectral measurements

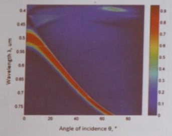


Zone 3, angle of incidence: 0°

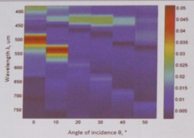


Zone 4 (500 nm), angle of incidence: 0°

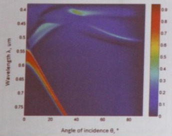
Spectral measurements in TM-polarized light



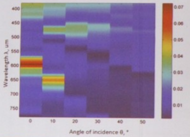
Zone 3
(400 nm)
TM-polarized
modelling



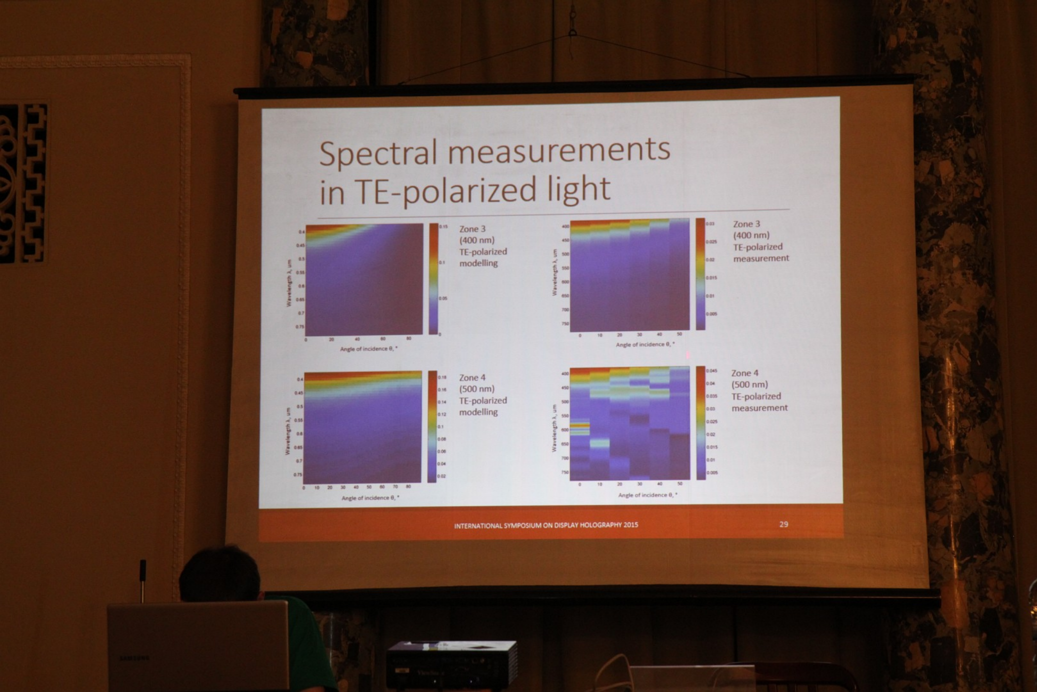
Zone 3
(400 nm)
TM-polarized
measurement



Zone 4
(500 nm)
TM-polarized
modelling



Zone 4
(500 nm)
TM-polarized
measurement


Spectral measurements
in TE-polarized light
Zone 3
(400 nm)
TE-polarized
modelling
Zone 3
(400 nm)
TE-polarized
measurement
Zone 4
(500 nm)
TE-polarized
modelling
Zone 4
(500 nm)
TE-polarized
measurement
Angle of incidence θ, °
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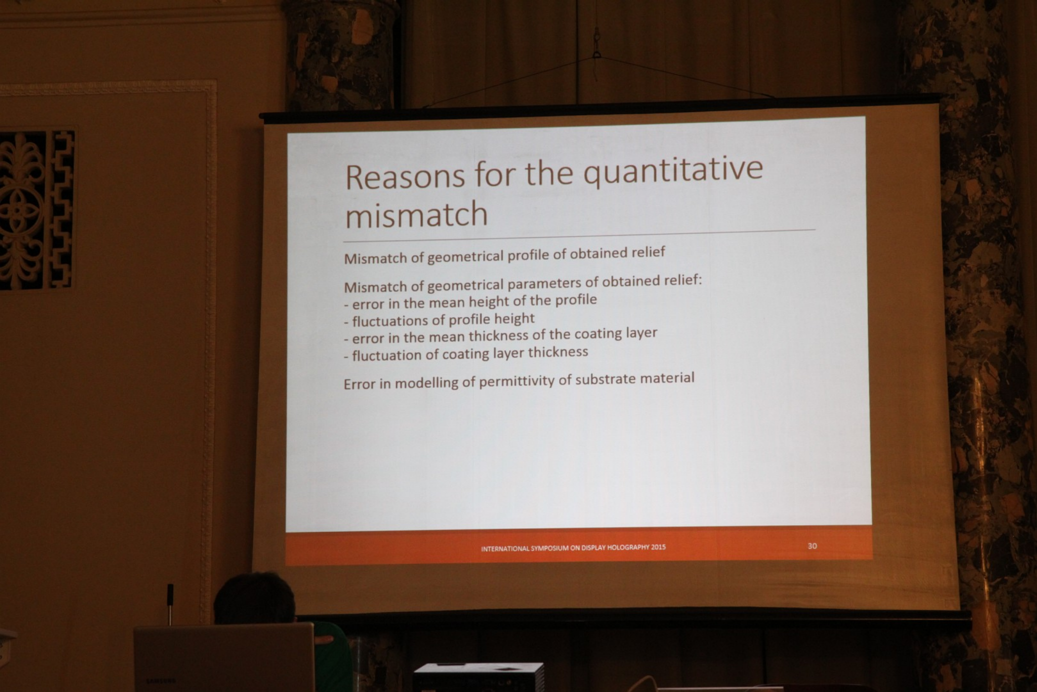
Reasons for the quantitative mismatch
Mismatch of geometrical profile of obtained relief
Mismatch of geometrical parameters of obtained relief:
- error in the mean height of the profile
- fluctuations of profile height
- error in the mean thickness of the coating layer
- fluctuation of coating layer thickness
Error in modelling of permittivity of substrate material
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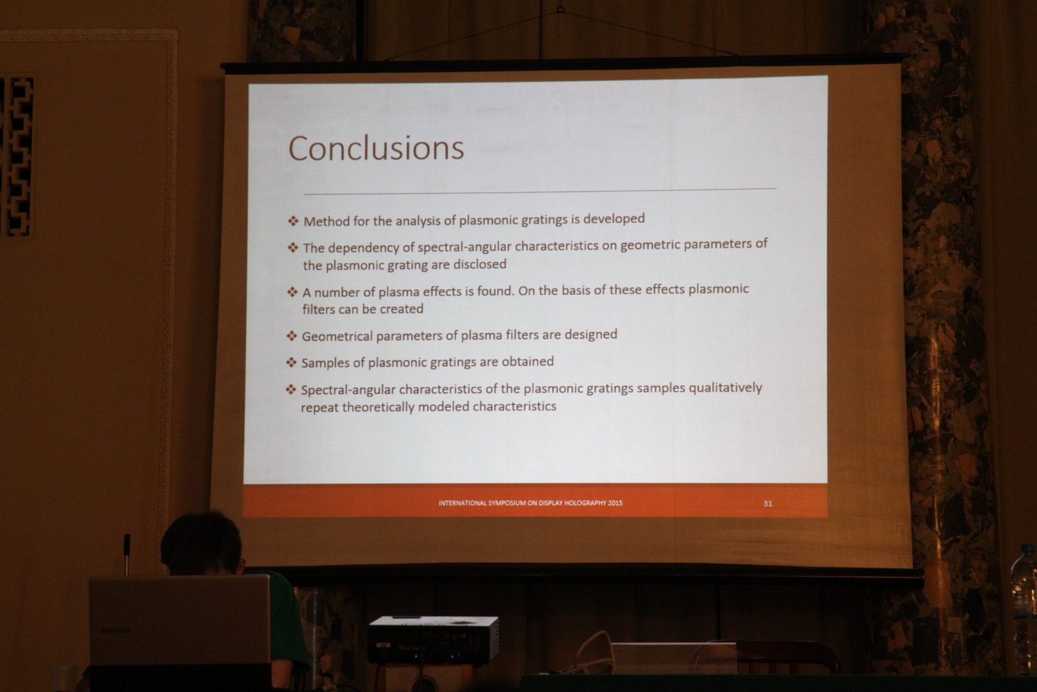
Conclusions
❖ Method for the analysis of plasmonic gratings is developed
❖ The dependency of spectral-angular characteristics on geometric parameters of the plasmonic grating are disclosed
❖ A number of plasma effects is found. On the basis of these effects plasmonic filters can be created
❖ Geometrical parameters of plasma filters are designed
❖ Samples of plasmonic gratings are obtained
❖ Spectral-angular characteristics of the plasmonic gratings samples qualitatively repeat theoretically modeled characteristics
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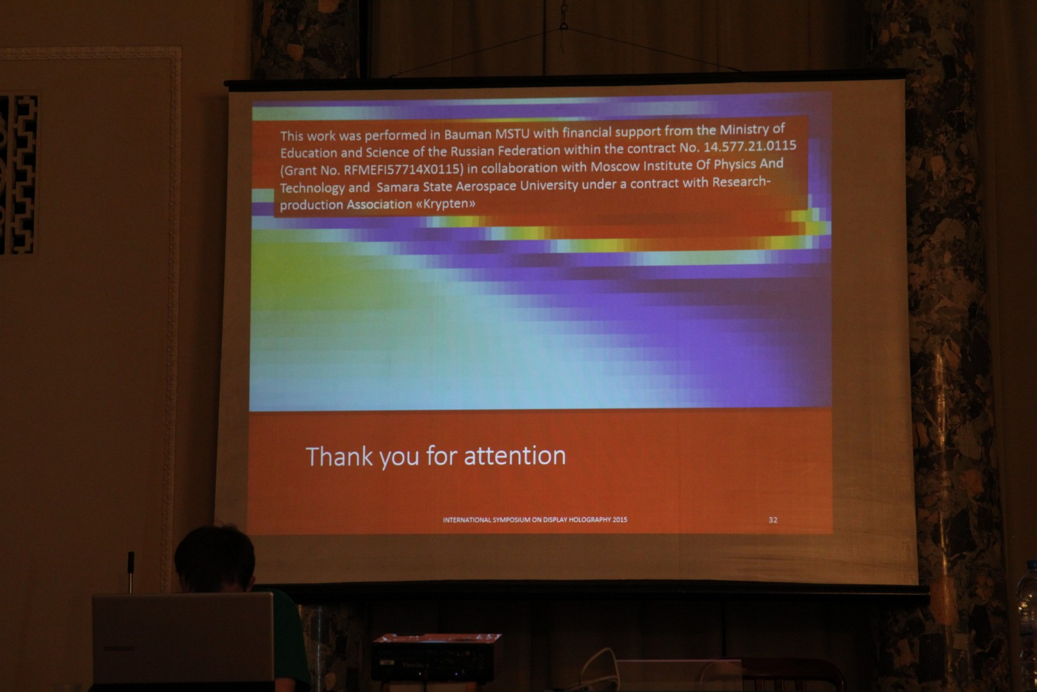

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Thank you for attention
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